

# An Integrated Assessment of China's Wind Energy Potential

Da Zhang, Michael Davidson, Bhaskar Gunturu,  
Xiliang Zhang and Valerie J. Karplus



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**For more information, contact the Program office:**

MIT Joint Program on the Science and Policy of Global Change

**Postal Address:**

Massachusetts Institute of Technology  
77 Massachusetts Avenue, E19-411  
Cambridge, MA 02139 (USA)

**Location:**

Building E19, Room 411  
400 Main Street, Cambridge

**Access:**

Tel: (617) 253-7492

Fax: (617) 253-9845

Email: [globalchange@mit.edu](mailto:globalchange@mit.edu)

Website: <http://globalchange.mit.edu/>

# An Integrated Assessment of China's Wind Energy Potential

Da Zhang<sup>\*†</sup>, Michael Davidson<sup>†§</sup>, Bhaskar Gunturu<sup>†</sup>, Xiliang Zhang<sup>\*</sup> and Valerie J. Karplus<sup>†</sup>

## Abstract

*Computable general equilibrium (CGE) models seeking to evaluate the impacts of electricity policy face difficulties incorporating detail on the variable nature of renewable energy resources. To improve the accuracy of modeling renewable energy and climate policies, detailed scientific and engineering data are used to inform the parameterization of wind electricity in a new regional CGE model of China. Wind power density (WPD) in China is constructed using boundary layer flux data from the Modern Era Retrospective-analysis for Research and Applications (MERRA) dataset with a 0.5° latitude by 0.67° longitude spatial resolution. Wind resource data are used to generate production cost functions for wind at the provincial level for both onshore and offshore, incorporating technological parameters and geographical constraints. By using these updated wind production cost data to parameterize the wind electricity option in a CGE model, an illustrative policy analysis of the current feed-in tariff (FIT) for onshore wind electricity is performed. Assuming a generous penetration rate, no grid integration cost and no interprovincial interconnection, we find that the economic potential of wind exceeds China's 2020 wind target by a large margin. Our analysis shows how wind electricity resource can be differentiated based on location and quality in a CGE model and then applied to analyze climate and energy policies.*

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<sup>\*</sup> Institute of Energy, Environment and Economy, Tsinghua University, Beijing, China.

<sup>†</sup> Joint Program on the Science and Policy of Global Change, Massachusetts Institute of Technology, Cambridge, MA, USA.

<sup>§</sup> Corresponding author (michd@mit.edu).

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## 1. INTRODUCTION

China's energy demand has grown by 150% over the past decade, making it the world's largest energy user. The majority of this growth has come from coal energy, which accounted for 70% of total primary energy use and 78% of electricity generation in 2011 (NBS, 2012; CEC, 2012). Estimated costs of air and water pollution in China range from 3–6% of China's annual economic output (World Bank and China SEPA, 2007). To reduce these adverse impacts and to combat climate change, China is actively scaling up deployment of renewable energy. China leads the world in installed capacity of renewable energy and in wind generation capacity (REN21, 2012). Growth in wind generation surpassed growth in coal-fired electricity for the first time ever in 2012 (CEC, 2013).

Integrating large shares of wind energy presents a new challenge for grid operators and policy-makers interested in meeting ambitious climate change mitigation goals. The inherent uncertainty in wind resource availability has the potential to drive up system-wide balancing costs, especially when the grid mix consists primarily of inflexible generation such as coal-fired power. In addition, the most economical resources are also highly distributed and often far from load centers, adding to costs of transmission infrastructure. These characteristics complicate analysis of both economy-wide and electricity sector-specific policy proposals currently under discussion in China.

Globally, the International Energy Agency estimates that over \$38 trillion of new energy infrastructure will need to be built through 2035 to meet growing demand (IEA, 2011). Because of the long construction and operational lifetimes of conventional power plants and transmission infrastructure, the choice of investments made in Beijing today will have a large impact on the future grid mix available to accommodate increasing renewable resource penetration. These policy decisions require sophisticated modeling techniques that incorporate economic, technical and resource constraints.

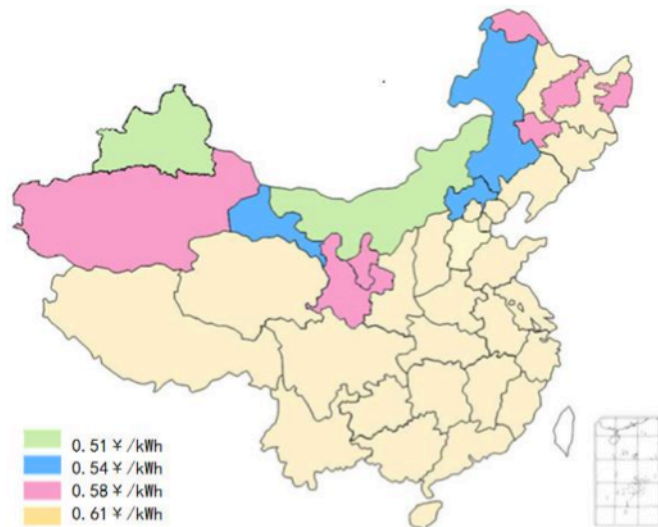
This report presents a novel method of analyzing climate policies using a computable general equilibrium (CGE) framework and detailed wind characterization using Modern Era Retrospective-analysis for Research and Applications (MERRA) data. The methodology is used to evaluate wind deployment in 2020 under China's current feed-in tariff levels. Technical, geographic and financial characteristics of wind projects are explicitly accounted for in provincial wind cost production functions. Offshore wind resources are also characterized, but are not incorporated into the CGE model, as these resources cannot be neatly apportioned among the 30 provinces represented in the model.

## 1.1 China's Renewable Energy Policies and Projected Deployment of Wind

China has experimented with a range of policy instruments to encourage renewable energy deployment and reform energy system institutions (IIP, 2012). China's National Renewable Energy Law of 2006 and regulations issued under it have established subsidies for wind, solar, and biomass deployment; public support for research and development; mandatory grid connection requirements; and a central fund supported by a nationwide electricity surcharge (NDRC, 2006; ERI, 2010; Kang *et al.*, 2012). China currently aims to install 200 gigawatts (GW) of wind and 50GW of solar photovoltaic by 2020 (see **Table 1**). In addition, it appears likely that China will implement renewable power quotas for major generators and grid companies, formulated as the percentage of total generation coming from non-hydropower renewable energy (Schuman & Lin, 2012). In this paper, we consider the impact of two existing central government incentives for wind: first, four regional feed-in tariff levels (see **Figure 1**); and second, preferential value-added tax (VAT) rates during the first several years of a project's life (Wang *et al.*, 2012).

**Table 1.** China's targets for renewable energy development through 2020. Sources: REN21 (2012), NEA (2012), NDRC (2012), State Council (2013).

Renewable energy targets	Grid-connected capacity (GW)		
	2012	2015	2020
<b>Wind</b>	62	104	200
<b>Solar PV</b>	3.1	35	50
<b>Biomass</b>	4.4	13	30



**Figure 1.** Wind feed-in tariffs included in this analysis (excluding sub-provincial variations, which are not incorporated).

## 1.2 Current State of Wind Connection and Integration Challenges

Electricity generating technologies place a number of constraints on efficient system operation. For conventional generators, maximum ramping rates and associated ramp costs, minimum shutdown and startup times, and output-dependent heat rates, among other properties, are important to consider in week-ahead planning. For renewable resources such as wind, solar and run-of-the-river hydropower, these include minimum and maximum output thresholds, as well as natural intermittency. Wind integration challenges arise from frequent ramping requirements and the unpredictability of wind resources interacting with the technical limits of conventional generators – conditions which lead to efficiency losses and grid stability concerns (Porter *et al.*, 2007).

Integrating renewable electricity into China's power grid has been a well-documented challenge. From 2006–2012, installed wind capacity expanded rapidly, but ensuring its contribution to the nation's energy generation mix has been less straightforward for technical, economic, and institutional reasons (Liu and Kokko, 2010). In general, policies have rewarded wind facility construction, offering only weak incentives to consider wind characteristics and grid connection challenges at the construction location. As a result, at the end of 2012, around 20% of wind generation capacity was not yet connected to the grid (CREIA *et al.*, 2013; CEC, 2013). In addition, grid-connected wind resources have seen decreasing capacity factors from curtailment. In 2012, while wind contributed only 2% of total electricity supply, around 20 TWh of wind was spilled – an effective curtailment rate of 17%, reaching 40–50% in some areas (CEC, 2013; NEA, 2013; Qi, 2013). By comparison, the Electricity Reliability Council of Texas (ERCOT), with roughly 8% wind penetration, saw a dramatic decline of wind curtailment rate from 17% in 2009 to less than 4% in 2012 (ERCOT, 2012; Wiser & Bolinger, 2013). In an attempt to strengthen oversight and ensure prompt grid connection, authority for project approval has been largely centralized (Xu and Alleyne, 2013).

Researchers and grid operators attempting to quantify the system-wide effects of increased renewable energy penetration have traditionally estimated costs in three ways: involuntary ramping of thermal units and other inflexible generation units, maintenance of additional reserves or backup capacity, and ancillary services such as frequency regulation. A survey of studies in the United States found additional ancillary service costs from increased wind penetration ranging from \$1–\$5/MWh, or up to 10% of wholesale generation costs (Porter *et al.*, 2007). Another large body of research focuses on optimal generation mixes as more renewable resources are brought online. A study of the resilience of the Chinese grid found a cutoff at around 26% penetration of wind into the grid (as a share of production), above which integration costs become limiting (Liu *et al.*, 2011).

Since these integration costs are not localized, there is considerable uncertainty in attributing them solely to wind power. In particular, existing methods tend to discount the inflexibility of conventional resources, leading some researchers to look for generalized metrics of “flexibility” for all generating types (Ma *et al.*, 2013). Coal, which accounts for 80% of China's electricity production and is projected to continue increasing in absolute terms, plays a large role in grid

integration challenges. As coal's relative share varies significantly by region – and is expected to decline nationally in response to nuclear, natural gas and large hydropower build-out – integration challenges will be highly contextual and location-specific.

### **1.3 Motivation for This Study**

The rapid increase of wind electricity generation in China expected over the next decade will face several hurdles, including siting and geographical concerns, grid connection and integration costs, and downward pressure on the price of displaced carbon-intensive energy. To assess policies addressing these concerns, CGE models offer advantages over partial equilibrium approaches for the electricity sector alone because they capture economy-wide effects (Lanz and Rausch, 2011). Commonly-used simplified CGE representations, however, may be inconsistent with technology and fuel substitution details afforded by a detailed bottom-up electricity sector model. Additionally, CGE models typically assume a representative profile for wind generation without differentiating resource quality by region. This study improves on the representation of wind resources and technology detail within a CGE framework to investigate wind electricity deployment dynamics in China.

## **2. LITERATURE REVIEW**

### **2.1 Previous Assessments of China's Wind Resources**

Detailed assessments of wind resources in China have only recently become available. The National Renewable Energy Laboratory (NREL) has several publicly available wind resource assessments that vary in terms of their geographic coverage. NREL (2007a) used satellite and upper-air measurements to construct 1-km<sup>2</sup> resolution maps of wind power density in eastern China. Elliott *et al.* (2002) included ground station measurements to construct 200-meter resolution maps of portions of southeastern China. NASA has conducted a global wind assessment with 1-degree spatial resolution (approx. 100 km × 80 km at mid-latitudes), providing average wind speeds (NASA, 2009). NREL (2007b) provides global offshore wind speed and wind power density at 0.25-degree resolution.

McElroy *et al.* (2009) used a data assimilation system on a five-year model output (2004–2008) from the Goddard Earth Observing System (GEOS-5) to reconstruct mean wind speed and wind power density maps of China at an 80-meter wind turbine hub height. The report calculated regional capacity factors and levelized costs of energy, and assessed electricity generation potential. However, due to the limited observation record available at the time, the paper could not account for interannual variability. Hong and Moller (2011) generated 1-km<sup>2</sup> resolution maps for feasible offshore wind potential based on NREL wind data, accounting for ocean depth.

### **2.2 General Equilibrium Approaches to Incorporating Intermittent Energy Sources**

CGE models treat electricity as a fungible commodity, with the same quality and value regardless of its primary energy source. These models do not consider engineering methods to track electricity flows, equate supply and demand instantaneously, or incorporate operational

characteristics of generating technologies. Therefore, additional information or alternative approaches are generally needed to capture the temporal variability of supply, which is especially important as the relative contribution of renewable electricity to total generation expands.

One such method is for the CGE model to treat renewable electricity as an imperfect substitute for conventional electricity generation (fossil fuel-based, nuclear and hydropower) with a rising resource input cost correlated with the availability and intensity of wind resources. This formulation provides one way of capturing the costs of intermittency and allows gradual penetration of renewables only as prices of other generation technologies rise (Paltsev *et al.*, 2005). A second method implemented in a CGE framework creates a piece-wise wind production function, modeling imperfect substitution at low penetrations and requiring back-up capacity (e.g., natural gas-fired) at high penetrations (Morris *et al.*, 2010). Additional approaches have been attempted, which include disaggregating the electricity commodity sector into several load blocks throughout the year (Rodrigues *et al.*, 2011). **Table 2** reviews these approaches in order of increasing model detail.

**Table 2.** Review of approaches to incorporate renewable energy characteristics in CGE models.

<b>Basic approach</b>	<b>Backup capacity</b>	<b>Cost penalty</b>	<b>Load blocks</b>	<b>Iterative model</b>
	Require additional flexible generation units (e.g., natural gas) that add to renewable generation costs	Unavailability and intermittency modeled as resource “cost” and substitution penalty of scaling up generation	Electricity is differentiated by time and region, according to demand and supply variability	Recursively run CGE and external power systems model to minimize bottom-up and top-down deviation
<b>Research application</b>	Morris <i>et al.</i> (2010), Paltsev <i>et al.</i> (2005)	Paltsev <i>et al.</i> (2005)	Rodrigues <i>et al.</i> (2011)	Rausch and Mowers (2012)
<b>→ Increasing technical detail and model coupling challenges →</b>				

### 2.3 Results of CGE Modeling Studies of China’s Energy and Climate Policies

This analysis contributes to a growing body of CGE modeling studies focused on the contribution of renewable electricity to low carbon development in China, which are part of a broader research agenda on the design of China’s energy and climate policy. Many studies have constructed CGE models that treat China as a single region to study the potential impact of climate and energy policies (see for example Cao, 2007; Wang *et al.*, 2009; Lin and Jiang, 2011; Dai *et al.*, 2011; Zhang *et al.*, 2013b). Zhang *et al.* (2013b) showed the importance of a CGE framework for assessing the impact of renewable policies, finding that displacing coal with subsidized renewable energy in the electric power sector put downward pressure on the coal price and lead to its increased use in other sectors, offsetting CO<sub>2</sub> emissions reductions. Zhang *et al.* (2013b) neither considered sub-national detail in the electricity system nor explicitly characterized wind resource based on historical observations. A new model that disaggregates



China at the provincial level, the China Regional Energy Model or C-REM, has been developed by the Tsinghua-MIT China Energy and Climate Project, and has been applied to assess energy cap and CO<sub>2</sub> intensity policies with targets differentiated by province (Zhang *et al.*, 2013a). In the present study, we augment this model with provincially-differentiated marginal cost curves based on a detailed spatial characterization of China's wind resources.

### **3. CHARACTERIZATION OF CHINA'S WIND RESOURCES**

#### **3.1 Re-analysis Methodology**

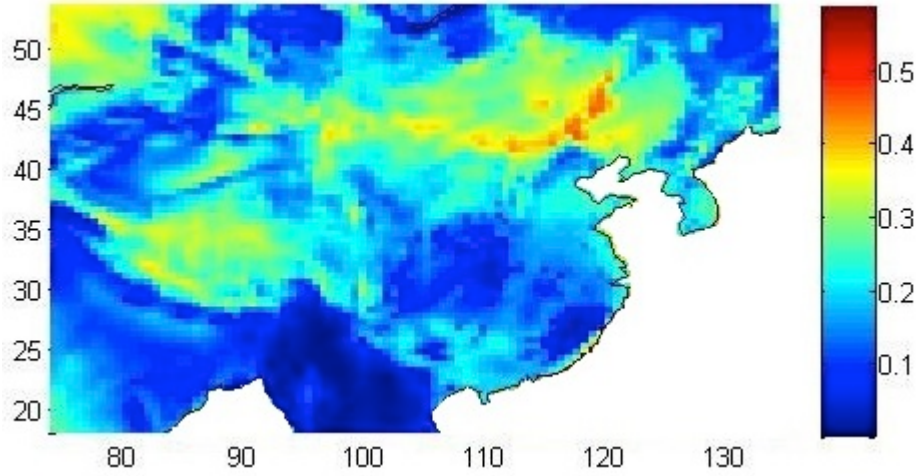
Recent wind assessments rely heavily on the method of retrospective analysis, or re-analysis. Building on the diverse collection of data measurements available from satellites, ground monitoring stations and upper-air balloons, re-analysis uses global circulation models to reconstruct complete wind profiles at sub-degree intervals over the span of decades (Rienecker *et al.*, 2011). These data account for multiyear variations in wind patterns and provide adequate geographic granularity for system-wide analysis.

This assessment uses Modern Era Retrospective-analysis for Research and Applications (MERRA) boundary layer flux data, a 31-year (1979–2009), high temporal resolution dataset measured in one hour increments. It was constructed using the GEOS-5 Atmospheric Data Assimilation System, which consists of the GEOS-5 model and interpolation analysis methods (Gunturu and Schlosser, 2011). Boundary layer similarity theory is used to compute China's offshore and onshore wind speeds, and characterize intermittency. The characterization was made at a variety of hub heights (only 80-meter is included here) at 0.5° longitude by 0.67° latitude resolution (approx. 56 km × 61 km at mid-latitudes).

Wind speeds at elevations relevant for wind turbines are strongly affected by atmospheric boundary layers and surface roughness. Assumptions of these parameters vary by study, but typically do not account for variations in seasons, terrain or stability in the atmosphere. The MERRA dataset captures a much longer timespan than typical studies (i.e., a single or limited number of years), which may better capture interannual variations such as the El Niño/La Niña cycles.

#### **3.2 Results of Wind Resource Assessment**

Wind power density is calculated at a hub height of 80 meters for each hour across the 31-year dataset. Low and high extremes of the wind resource face threshold and curtailment constraints, respectively. A power curve translates a given wind power density into actual electricity generation for a given design and size of turbine, taking into account these cut-offs as well as the non-linear performance of turbine generators. This paper uses power curves from a Sinovel 1.5-MW wind turbine (SL1500/82) for onshore generation, and a Sinovel 5-MW turbine (SL5000/128) for offshore generation. For each hour and grid cell, expected electricity generation is divided by the theoretical maximum to calculate the capacity factor, which is then averaged at all hours in the 31-year dataset to account for interannual variation (see **Figure 2**).



**Figure 2.** Capacity factors for 1.5-MW onshore turbine in Mainland China. Grid size: 0.5° latitude by 0.67° longitude.

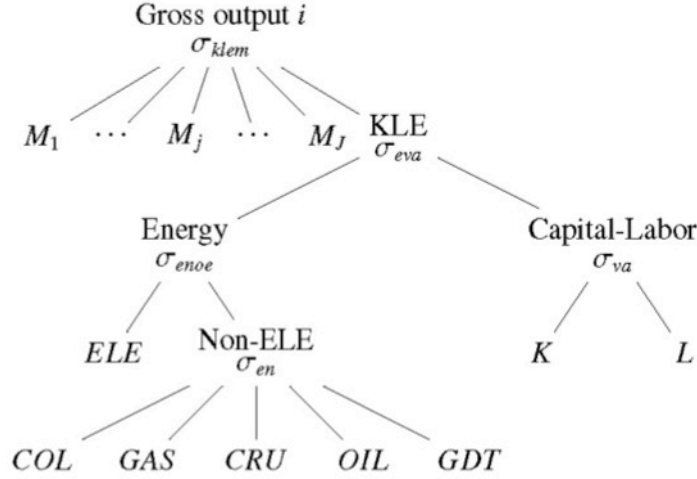
## 4. MULTI-REGIONAL COMPUTABLE GENERAL EQUILIBRIUM MODEL OF CHINA

### 4.1 Model Overview

For this study we use the China Regional Energy Model (or C-REM) described in Zhang *et al.* (2013a). The C-REM is a computable general equilibrium model based on the optimizing behavior of economic agents. Consumers maximize welfare subject to budget constraints and producers combine intermediate inputs and primary factors at lowest cost to produce output. Energy resources are primary factors and emissions of carbon dioxide (CO<sub>2</sub>) associated with their use are explicitly captured in the model. The model is formulated as a mixed complementarity problem (MCP) and solved using MPSGE (Mathiesen, 1985; Rutherford, 1995). Activity levels and prices satisfy zero-profit and market-clearance conditions<sup>1</sup>.

The model describes the production of energy and other goods by nested constant-elasticity-of-substitution (CES) production functions. Production inputs include labor, capital, natural resources (coal, natural gas, crude oil and land), and intermediate inputs. For all non-energy goods, the CES production functions are described by the nested structure in **Figure 3**. The top-level nest combines an aggregate of capital, labor, and energy inputs (KLE) with material inputs (M); the second-level nest combines energy inputs (E) with a value-added composite of capital and labor inputs (VA) in the KLE-nest; the third-level nest captures the substitution possibilities between electricity (ELE) and final-energy inputs (FE), represented in the fourth-level nest: coal (COL), natural gas (GAS), gas manufacture and distribution (GDT), crude oil (CRU) and refined oil products (OIL).

<sup>1</sup> The model is formulated in the mathematical programming system MPSGE (Rutherford, 1999), a subsystem of GAMS, and solved using PATH (Dirkse and Ferris, 1995).



**Figure 3.** Nesting structure of CES production functions for non-energy goods.

All industries are characterized by constant returns to scale and are traded in perfectly competitive markets. Capital mobility is represented in each sector by following a putty-clay approach in which a fraction of previously installed capital becomes non-malleable in each sector. The rest of the capital remains mobile and can be shifted to other sectors in response to price changes. The modeling of international trade follows Armington's approach of differentiating goods by country of origin (Armington, 1969): goods within a sector and region are represented as a CES aggregate of domestic and imported goods with associated transport services; goods produced within China are assumed to be closer substitutes than goods from international sources, replicating a border effect.

Final consumption in each region is determined by a representative agent who maximizes consumption subject to a budget constraint. Consumption is represented as a CES aggregate of non-energy goods and energy inputs and the budget constraint is determined by factor and tax incomes with fixed investment and public expenditure.

## 4.2 Database and Aggregation

The model is built on a comprehensive energy–economic dataset which includes a consistent representation of energy markets in physical units, as well as detailed accounts of regional production and bilateral trade for the year 2007. The dataset is global, but includes regional detail for China's provinces. The global data (not including China) comes from the database version 8 of the Global Trade Analysis Project (GTAP, 2012). The GTAP 8 data set identifies 129 countries and regions and 57 commodities (Narayanan *et al.*, 2012) and provides consistent global accounts of production, consumption and bilateral trade as well as consistent accounts of physical energy flows, energy prices and emissions in the year 2007. As we are mainly interested in the sub-national impacts in China, we aggregate the international data to three regions (USA, Europe, and the rest of the world).

The data for China are based on China’s national input-output table and the full set of China’s provincial input-output tables published in 2007 (National Statistics Bureau of China, 2011), which specifies benchmark economic accounts for 30 provinces in China (Tibet is not included due to a lack of data and the small scale of its economic activities). Energy use and emissions data are based on the 2007 China Energy Statistical Yearbook (National Statistics Bureau of China, 2008). The model explicitly represents six energy sectors and 10 non-energy composites<sup>2</sup>. Zhang *et al.* (2013a) describe in detail the method used for balancing the Chinese data set and merging it with the global dataset. Elasticities of substitution are adopted from the GTAP 8 database, as well as from the MIT Emissions Prediction and Policy Analysis model (Paltsev *et al.*, 2005), in particular for the price elasticity of supply of nuclear and hydropower. Wind is represented as described below.

### 4.3 Representation of Electricity Sector

In the C-REM model the production of energy goods is separated into fossil fuels, refined-oil products, gas manufacture and distribution, and electricity production. The production of fossil fuels (COL, GAS, CRU) combines sector-specific fossil-fuel resources with a Leontief (fixed-proportion) aggregate of intermediate inputs and a composite of primary factors and energy. This composite is described by a Cobb-Douglas function of energy inputs, capital, and labor. Refined-oil products (OIL) and gas manufacture and distribution (GDT) are described similarly to the production of other goods, but with a first-level Cobb-Douglas nest combining the associated fossil-fuel inputs (crude oil for oil refining; crude oil, coal, and natural gas for gas manufacture and distribution) with material inputs and the capital-labor-energy (KLE) nest. Electricity production is described by a Leontief nest which combines, in fixed proportions, several generation technologies, including nuclear, hydro, and wind power, as well as conventional power generation based on fossil fuels. Non-fossil-fuel generation is described by a CES nest combining specific resources and a capital-labor aggregate.

To model spatial variability of wind, we take the general approach of Paltsev *et al.* (2005), adding a “resource cost” to the wind power production structure, reflecting resource data on usable wind electricity generation. Each province has a unique wind resource supply curve based on its wind resources characterized in Section 3.2. The increasing marginal cost of wind deployment within a region corresponds to a decreasing marginal capacity factor as preferred wind resources are consumed.

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<sup>2</sup> The energy goods include coal (COL), crude oil (CRU), refined-oil products (OIL), natural gas (GAS), gas manufacture and distribution (GDT) and electricity (ELE); the non-energy sectors include agriculture (AGR), minerals mining (OMN), light industries (LID), energy-intensive industries (EID), transport equipment (TME), other manufacturing industries (OID), water (WTR), trade (TRD), transport (TRP) and other service industry (OTH).

## 4.4 Calculating Wind Cost Production Curves

Using the detailed grid-cell data on capacity factors, the marginal cost of wind is represented as a function of expanding generation to exploit less favorable resources. To develop wind supply curves by province, information on wind availability from the above analysis is combined with information about geographical constraints on usable land area for turbine construction. The production cost is calculated using the common metric, levelized cost of energy (LCOE), which represents the cost of the electricity generated over the life of the turbine. The following two sections describe how this information is integrated to yield an assessment of the cost of wind generation expansion by province.

### 4.4.1 Wind Electricity Cost Model

We employ a standard calculation for the LCOE of wind electricity, which is performed for every grid cell using its unique capacity factor generated from the above wind resource analysis. **Table 3** describes the cost model assumptions.

**Table 3.** Key assumptions used in the wind cost model.

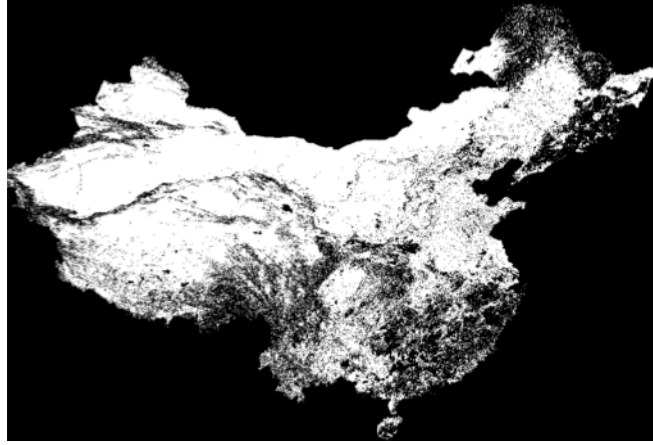
Model input	Assumption used in present analysis
Debt-equity ratio	80/20
Rate of return	10%
Capital cost	10.5 mil RMB per 1.5MW turbine
Operations and maintenance costs	100 RMB / MWh
Tax	VAT (8.5%) + EIT (0%, $t \leq 3$ ; 12.5%, $3 < t \leq 6$ ; 25%, $t > 6$ ) VAT plus VAT surcharge is applied on equipment
Loan	Interest rate = 6.2% over 15 year term, payment starting from year 3
Depreciation starting year	4

The cost calculation is based on a Sinovel 1.5-MW wind turbine that has a total capital cost of 10.5 million RMB, including equipment cost and other costs (e.g. land rental, permitting services, and other one-time costs). As in other studies (e.g., McElroy *et al.* (2009)), we assume an 80/20 debt-to-equity ratio and a required rate of return of 10%. Operations and maintenance costs are assumed to be 0.1 RMB per kWh generated. This study assumes loan payments start from year 3 (the year after loans are taken out) and that depreciation of the project equity starts from year 4. These assumptions have very little impact on the overall cost.

### 4.4.2 Physical Constraints

Urban areas, slopes greater than 10%, geographic features such as lakes and rivers, and major industrial and transportation facilities are not considered for siting. An exclusion map of unavailable locations for wind turbines was constructed in the ArcGIS platform using 30-

arcsecond elevation data from NASA’s Shuttle Radar Topography Mission and a land-cover classification for China from satellite remote sensing (USGS, 2004; Liu *et al.*, 2003). White areas in **Figure 4** indicate land available for onshore turbine construction. For offshore turbines, areas within 100km of the coast with depths shallower than 50 meters are considered suitable for construction. This analysis does not account for offshore exclusion zones such as areas used for shipping or fishing.



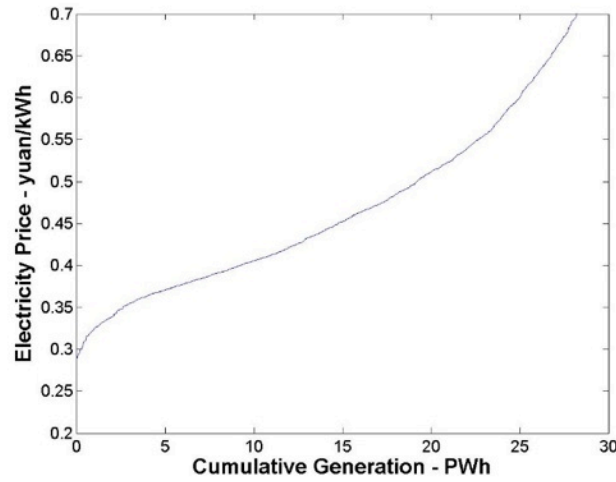
**Figure 4.** Available areas for onshore wind turbine construction (white). Grid size: 30-arcsecond ( $\sim 1\text{km}^2$  at mid-latitudes).

Assumptions about optimal turbine spacing also significantly affect the total estimated wind generation. Much research has been devoted to determining the maximum allowable density of wind turbines in a farm before the effective power of downstream turbines is reduced. Standard practices such as 3–5 rotor diameter spacing cross-wind and 5–9 diameter spacing upwind have been used historically (Masters, 2004).; however, power fall-off at turbine spacing of 7 and 10 rotor diameters has been experimentally observed (Hirth & Schroeder, 2013. Meyers & Meneveau (2012) concluded that the commonly used spacing of 7 rotor diameters by wind developers may be suboptimal, and recommended a turbine spacing of around 15.

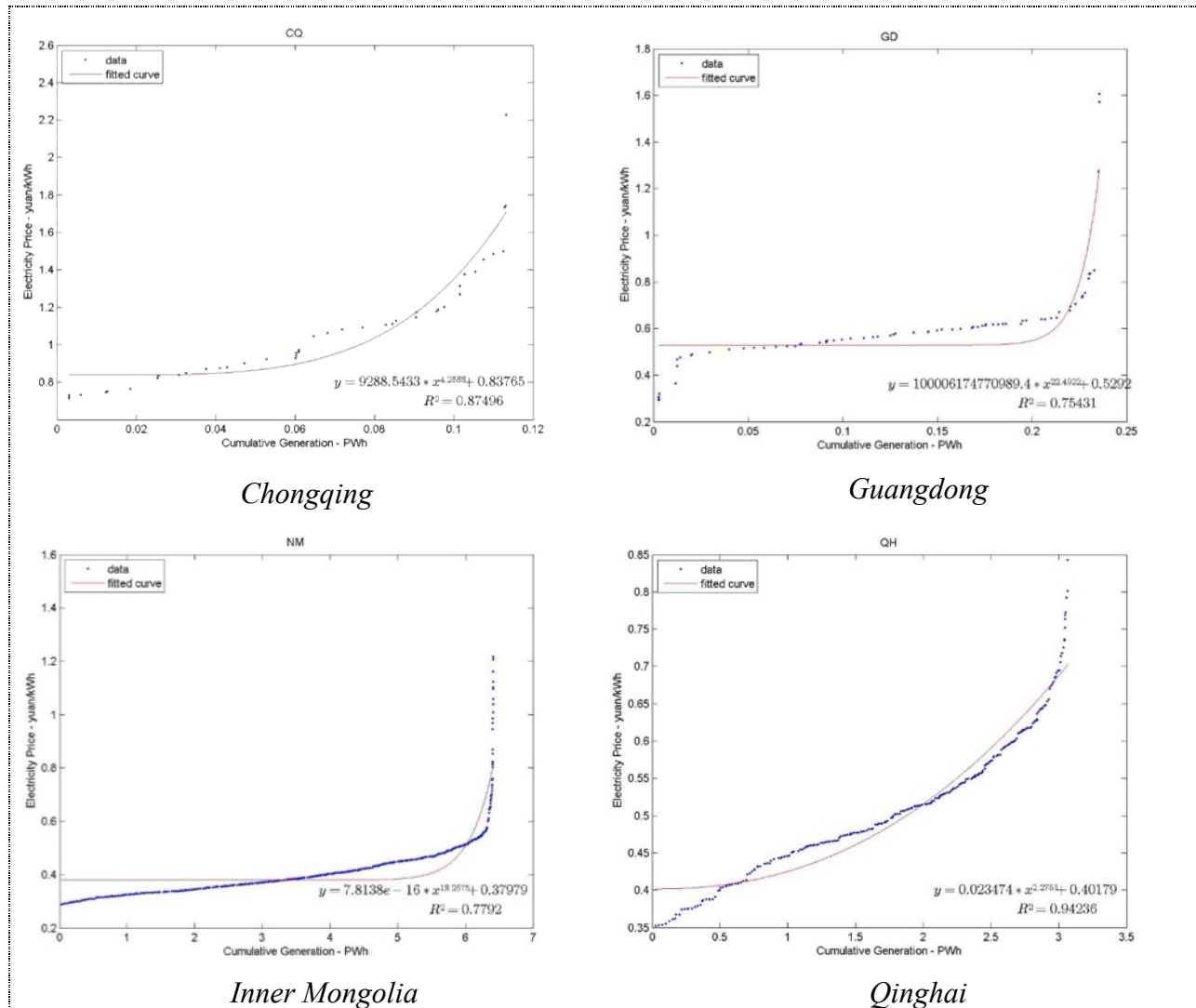
In this paper, for onshore wind, we use the turbine spacing based on a survey of twelve existing wind farms in China, ranging from  $1.5\text{MW}/\text{km}^2$ – $4.5\text{MW}/\text{km}^2$ . We select  $2.58\text{MW}/\text{km}^2$  as a representative spacing – equivalent to  $0.58\text{km}^2$  area per turbine, or roughly  $9 \times 9$  rotor diameter spacing. For offshore wind, we investigate three existing and planned projects in China ranging from  $4.5$ – $5.6\text{MW}/\text{km}^2$ , and choose  $5\text{MW}/\text{km}^2$  as a representative spacing.

#### 4.4.3 Wind Production Costs

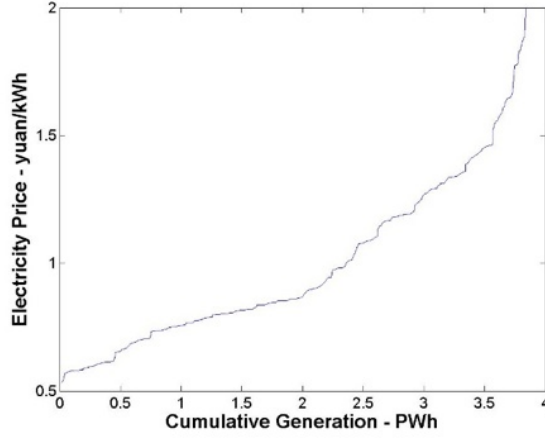
The supply cost curves for wind electricity are shown nationally, in select provinces, and offshore in **Figures 5, 6, and 7**, respectively, with each fitted to power curves for later analysis. The supply curves exhibit distinct characteristics within provincial borders, indicating the heterogeneous availability of wind resources. The shape and magnitude of these supply curves also varies significantly across provinces (see Figure 6).



**Figure 5.** National onshore wind production cost curve (RMB / kWh vs. PWh).



**Figure 6.** Select provincial wind production cost curves (RMB / kWh vs. PWh).



**Figure 7.** National offshore wind production cost curve (RMB / kWh vs. PWh).

## 4.5 Representing Wind Resource and Cost Detail in the C-REM Model

### 4.5.1 Elasticity of Substitution

We introduce wind cost into a top-down representation of the electricity sector in each of China's provinces. We discuss here how we model wind as a backstop technology using a CES function and discuss special treatment for individual provinces below, in Section 4.5.2. In the CES formulation, the electricity sector is modeled as a representative firm that minimizes production costs subject to technological, market, and resource constraints, which are defined by its associated CES function. The contribution from wind generation at time  $t$  in region  $r$  is given by the (zero-profit) condition:

$$p_{t,r} \geq \left\{ \theta_r (\mu_r \cdot p_{w,t,r})^{1-\sigma_r} + (1 - \theta_r) (\mu_r \cdot p_{k,t,r})^{1-\sigma_r} \right\}^{\frac{1}{1-\sigma_r}} \quad (1)$$

The price of wind electricity output,  $p_{t,r}$ , is treated as a fungible commodity with other electricity types.  $\theta_r$  is the cost share of the wind resource by province, while  $p_{w,t,r}$  is the variable wind resource price.  $\sigma_r$  is a region-specific elasticity of substitution between the wind-resource and other inputs – in this case, capital – denoted by  $k$ .  $\mu_r$  is a markup factor defined by the ratio of the marginal cost of the first kWh of delivered wind electricity and the base-year marginal cost of the benchmark electricity generation technology. In reality, new generation technologies scale up gradually even when the economics are favorable. To replicate this behavior in the model, we parameterize a technology-specific fixed factor that expands as a function of production in the previous period. However, this factor remains constrained by its value and the ability to substitute between it and other inputs, which is defined by  $\sigma_r$  above.

The detailed provincial-level wind cost information enters the model through  $\sigma_r$ , which is calibrated by fitting a power function to the LCOE supply curves derived above. First, the price elasticity of supply is estimated using the relationship:

$$\ln(q_{r,k}) = \alpha + \epsilon_r \log(LCOE_{r,k}) + \epsilon_{r,k} \quad , \quad (2)$$



where  $k$  is a wind site located within region  $r$ ,  $q_{r,k}$  is the electricity output, and  $\epsilon_r$  is the price elasticity of wind power supply by province;  $\alpha$  is a constant and  $\epsilon_{r,k}$  is the regression error term. The elasticity of substitution by province that characterizes the relationship between resource factor and other inputs is as follows:

$$\sigma_r = \frac{\epsilon_r}{\alpha} \quad (3)$$

This substitution elasticity  $\sigma_r$  is incorporated into the CES nest representing wind generation technology for every province in China. With heterogeneity in wind resource availability and cost represented in the model, we can forecast baseline generation and the impacts of policy. In the following section, we consider a simulation of a feed-in tariff for wind electricity generation.

#### 4.5.2 Backstop Technology Criteria

Wind energy is formulated as a backstop technology in our CGE model. This category is typically used for new technologies that may be turned on or off depending on policy or other constraints, such as technology availability. For simplicity, the wind backstop technologies only use two inputs: capital and wind resource. The initial value share of the wind resource is set to 0.2.

Two criteria are used to parameterize the wind backstop: the cost of harvesting the wind resource relative to electricity tariffs and the provincial FIT, and a cap on wind penetration in each province at 20% of generation. The latter is used as a proxy for issues of grid integration discussed in Section 1.2, and was assigned within a reasonable range of current and projected curtailment rates (Liu *et al.*, 2011). Other systems, such as the wind-rich state of Texas, see curtailment issues (though less severe than in China) at much lower penetrations rates of approximately 8–9%. An intermediate value of 20% was chosen for the maximum penetration allowed since we expect that, long-term, transmission capacity will increase and demand will grow in regions close to wind, alleviating some of the current congestion. Further study based on detailed power systems models is needed to improve this approximation.

Feed-in tariffs for each province as shown in Figure 1, a default electricity tariff of 0.5 RMB / kWh, and the cost curves in Section 4.4.3 are used to categorize the wind representation in the CGE. For provinces with multiple FITs, the lowest is used. The criteria for the wind backstop technology chosen for each province are as follows:

1. Provinces with wind potentials below the electricity tariff, with at least 20% of total annual generation: Beijing, Gansu, Hebei, Heilongjiang, Inner Mongolia, Jilin, Jiangsu, Liaoning, Ningxia, Qinghai, Shaanxi, Shandong, Shanxi, Sichuan, Tianjin, Xinjiang and Yunnan. For these provinces, we model a Leontief backstop technology ( $\sigma_r = 0$ ) that represents wind potential below the electricity tariff, and the 20% cap becomes binding.
2. For provinces with wind potentials below the electricity tariff and with less than 20% of total annual generation, we further differentiate:

- a. Provinces with wind potentials above the electricity tariff where the only cost level of potential wind resource falls below the feed-in tariff and corresponds to a single grid cell that is cost-competitive with subsidy; provinces with several cost levels falling between the electricity tariff and feed-in tariff where the lowest cost level can reach 20% of total annual generation (i.e. supply elasticity is infinite): Fujian, Hainan and Shanghai. For these provinces, we model one Leontief backstop technology representing the wind potentials below the electricity tariff, and a second Leontief backstop technology representing the wind potentials between the electricity tariff and feed-in tariff. The second backstop technology receives feed-in tariffs.
  - b. Provinces with several cost levels of wind potentials between the electricity tariff and feed-in tariff where the lowest cost level cannot reach 20% of total annual generation (i.e. supply elasticity is a positive number): Guangdong, Guangxi, Guizhou, Henan, Hunan and Zhejiang. For these provinces, we model one Leontief backstop technology representing the wind potentials below the electricity tariff, and one CES backstop technology representing the wind potentials between the electricity tariff and feed-in tariff. The elasticity of substitution between capital and wind resource ( $\sigma_r$ ) is calculated following the methods described in Rausch and Mowers (2012) (also discussed in the previous section). The CES backstop technology receives feed-in tariffs.
3. For provinces with no wind potential below the electricity tariff but with wind potential below the feed-in tariff level, we further differentiate:
    - a. Provinces where the only cost level of potential wind resource falls between the electricity tariff and feed-in tariff, corresponding to a single grid cell that is cost-competitive with subsidy (i.e. supply elasticity is infinite): Jiangxi. We model one Leontief backstop technology representing the wind potentials between the electricity tariff and feed-in tariff. This backstop technology will receive feed-in tariffs.
    - b. Provinces with several cost levels of wind potentials between the electricity tariff and feed-in tariff (i.e. supply elasticity is a positive number): Anhui. We model one CES backstop technology representing the wind potentials between the electricity tariff and feed-in tariff.
  4. Provinces with no wind potential below the feed-in tariff level: Chongqing and Hubei. The backstop technology for wind is not turned on in this model.

Threshold values used to characterize wind resource availability at the provincial level, along with its their relationships to wind costs and the impact of a feed-in tariff, are detailed in **Table 4**.

**Table 4.** Threshold values of wind resources by province used in CGE model. An electricity tariff of 0.5 RMB / kWh was used for all provinces.

\* Only for provinces with wind potential below the electricity tariff and with less than 20% of total annual generation.

\*\* Province has only one grid cell with wind potential between the electricity tariff and the FIT.

Province	20% of annual power generation (TWh)	Wind potential below tariff (TWh)	Lowest cost below FIT (RMB/kWh) *	Wind potential at this lowest cost (TWh) *	Supply elasticity for wind potential between tariff and FIT *	
Anhui	17.4	0	0.57	6.7	0.4	**
Beijing	4.5	4.5				
Chongqing	7.3	0	N/A	-	-	
Fujian	20.8	20.0	0.51	8.7	∞	**
Gansu	12.4	581				
Guangdong	53.9	29.6	0.51	10.3	1.2	**
Guangxi	13.7	10.8	0.51	0.3	3.1	**
Guizhou	22.8	4.3	0.51	1.2	1.9	**
Hainan	2.3	2.1	0.51	0.4	∞	**
Hebei	32.9	420				
Henan	37.3	4.5	0.52	0.3	0.4	**
Heilongjiang	14.0	867				
Hubei	30.9	0	N/A	-	-	
Hunan	16.7	2.0	0.51	0.1	1.9	**
Inner Mongolia	36.6	5850				
Jilin	10.0	572				
Jiangsu	56.5	63				
Jiangxi	9.9	0	0.58	10	∞	**
Liaoning	22.3	505				
Ningxia	9.1	79				
Qinghai	6.0	1794				
Shaanxi	12.9	239				
Shandong	51.9	336				
Shanghai	14.8	10.0	0.58	4.5	∞	**
Shanxi	35.2	267				
Sichuan	24.5	119				
Tianjin	8.0	18.6				
Xinjiang	8.4	2798				
Yunnan	18.1	42				
Zhejiang	41.6	6.5	0.52	3.6	3.5	**

## 5. CGE MODELING RESULTS

The feed-in tariff for wind was established in 2009 and is the primary policy instrument China has used to expand wind electricity. We apply C-REM with detailed wind characterization by province to assess the impact of a feed-in tariff on future wind electricity generation under the emissions intensity targets with a national allowance trading scheme in China. We simulate the optimal economic contribution of wind to the electricity generation mix by province.

The provincial results of wind generation are in **Table 5**. We find that long-run projected nationwide wind electricity generation is approximately 508 TWh, higher than China's 2020 target (about 400 TWh, assuming a national average capacity of 20%). 68% of this comes from provinces with significant wind resources that are already cost-competitive using the above criteria. We suggest that the national total be interpreted with caution and in view of the modeling assumption employed—namely, a cap on 20% of generation from wind at the provincial level. Therefore, though Xinjiang has a rich, cost-competitive wind resource potential (2798 TWh), it is assumed that only 20% (7.9 TWh) of Xinjiang's total load can be met by wind.

**Table 5.** Long-term contribution of wind to provincial electricity generation with the feed-in tariff.

Province	Generation (TWh)	Province	Generation (TWh)
<i>Provinces with &gt;20% generation below electricity tariff (20% cap is binding)</i>		<i>Provinces with &gt;0% and &lt;20% generation below electricity tariff (additional wind can be supported by FIT)</i>	
Beijing	4.3	Fujian	27.7
Gansu	11.7	Guangdong	43.2
Hebei	31.2	Guangxi	12.0
Heilongjiang	13.3	Guizhou	6.4
Inner Mongolia	34.5	Hainan	2.4
Jilin	9.5	Liaoning	21.1
Jiangsu	53.9	Ningxia	8.8
Liaoning	21.1	Hunan	2.0
Ningxia	8.8	Shanghai	13.2
Qinghai	5.6	Zhejiang	35.8
Shaanxi	12.3	<i>Provinces with no wind potential below electricity tariff</i>	
Shandong	50.0	Anhui	6.3
Shanxi	33.1	Jiangxi	8.9
Sichuan	23.7	<i>Provinces with no wind potential below feed-in tariff</i>	
Tianjin	7.6	Chongqing	0
Xinjiang	7.9	Hubei	0
Yunnan	16.9		
		<b>China</b>	<b>508.0</b>

Furthermore, we find some provinces with wind resources that are only cost-competitive under a FIT scheme, namely: Anhui and Jiangxi. Intermediate provinces—where some wind is below the electricity tariff, but additional wind can be supported under a FIT—include: Fujian, Guangdong, Guangxi, Guizhou, Hainan, Hunan, Shanghai and Zhejiang.

Notably, in this paper we do not include the grid integration cost of wind, which could significantly bring down the economic potential for wind installation in China.

## **6. CONCLUSIONS**

This report has demonstrated how detailed scientific characterization of the onshore wind resource for China can be incorporated into a provincially-disaggregated model and used to assess the impact of policy options for promoting renewable electricity expansion. The main methodological contribution of this paper is to demonstrate how detailed scientific information can be used to differentiate wind resource by location and quality, which can then be represented within a CGE framework. We apply this framework to investigate the impact of a FIT in China—an important current policy issue.

### **6.1 Preliminary Implications for Policy**

This analysis provides a platform that, with appropriate refinements, can address several important policy questions. We find that China's wind resources are concentrated in a handful of provinces, which provide for an abundance of installation opportunities to meet China's 2020 wind target, even under restrictive penetration rates.

In several provinces, the FIT policy we investigate here does not play a key role in incentivizing the deployment of wind; in other provinces, no wind is constructed at all. This suggests that additional parameters such as costs of curtailment and the operational benefits of transmission interconnection need to be investigated in more detail, which requires new methods for incorporating engineering and resource data into a CGE framework. Future research may identify robust decision strategies for generation and transmission expansion planning.

On the other hand, in provinces that have significant loads but moderate wind resources, the FIT is shown to have a critical role in deploying wind. From the perspective of reducing the impacts of intermittency, these provinces (such as Guangdong, Fujian and Zhejiang) are good locations – they have significant loads and do not require expensive transmission investments to integrate wind.

### **6.2 Caveats and Future Work**

We recognize that the modeling framework presented makes several noteworthy assumptions that may produce misleading estimates of economically-viable resource, despite efforts to capture realism in resource availability and the cost of wind electricity development. These influences can be divided into static and dynamic factors, and represent the richness of possibilities for future work in this area.

Static factors are those that affect the equilibrium amount of wind electricity in a static CGE model such as the one presented (a snapshot of the economy in equilibrium). These include:

1. **Intermittency.** Wind generation is not a perfect substitute for fossil-fuel generation because of its intermittent nature. Given the existing generation mix, there is an upper limit of wind introduction to the grid if there is no back-up capacity for wind. This will increase the cost of wind significantly, and as such will be left for future study. Here, we set this upper limit as 20% of total annual generation by province, though other values could be used.
2. **Curtailment.** Related to intermittency, curtailment (when grid operators choose to spill wind generation for grid stability and other reasons) results in foregone revenue to wind generators. As this was roughly 17% of all usable wind generation in 2012, curtailment has a large impact on the financial performance of wind projects.
3. **Grid connection.** Wind farms typically require some additional transmission infrastructure to reach a substation – as much as several kilometers. These costs are highly location-specific and the cost allocation does not follow transparent guidelines. As wind farms may be non-operational for the first year or more before connections are established, this also represents an opportunity cost for developers.
4. **Limited inter-provincial electricity transfers.** Wind resources can contribute to electricity supply across provincial borders, but significant challenges exist to strengthening regional interconnections in the Chinese power sector. This model does not allow for these transfers which, if incorporated, would reduce the cost of generating wind power by relaxing the 20% binding cap on wind penetration, especially in wind-rich provinces.

There is reason to believe that a static model, representing a single snapshot in time, cannot reproduce exactly the quantities and prices in an active economy. To better understand the limits to wind power growth, certain dynamic factors should be considered for future work:

1. **Financing.** Capital is required to build new installations for wind. However, in reality, a fraction of previously-installed capital becomes non-malleable in each sector of the economy and can be even higher for the electricity sector in the short term (roughly 5–10 years). In our scenario, which reflects long-term wind development, no vintaging of the capital stock is modeled.
2. **Project approval.** The central government is trying to control the rapid growth rate of wind, because of the decreasing capacity factors observed and poor connection rates. As of 2011, all new wind power projects must be approved by the National Energy Administration to qualify for the FIT, which may have a dampening effect on installations (NEA, 2011).
3. **Production capacity.** In reality, new generation technologies scale up gradually even when the economics are favorable. To replicate this behavior in a dynamic model, a

technology-specific “fixed factor” is included as an input to production that expands according to production in the previous period.

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